# Modeling and Monitoring Effects of Area Burned and Fire Severity on Carbon Cycling, Emissions, and Forest Health and Sustainability in Central Siberia

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**Modeling and Monitoring Effects of Area Burned and Fire Severity on Carbon Cycling, Emissions, and Forest Health and Sustainability in Central Siberia**


## ABSTRACT

Boreal forests are extremely important globally, both for their large amount of carbon storage, and as a largely unexploited source of wood fiber. Changes in land use, cover, and disturbance patterns in boreal forests can impact fire regimes and forest health, global carbon budgets, atmospheric chemistry, and wood supply. One of the key disturbance processes in these systems is fire, which affects about 12-15 million ha of closed boreal forest annually, most of it in Eurasia. This exceeds the annual area harvested or disturbed by other natural agents, such as insects.

The Russian boreal forest contains about 25% of the global terrestrial biomass, yet data on the extent and impacts of fire in these forests are scarce and often contradictory. Several recent papers indicate that the impacts on terrestrial carbon storage of fires in boreal forest regions have been vastly underestimated. Furthermore, changes in land management and land use practices, regional climate, and fire suppression capability will affect fire risk and ecosystem damage from fires in ways that are poorly understood. In changing environments, fire can be a key agent to accelerate changes toward new ecosystem conditions. Improved understanding of the landscape extent and severity of fires and of factors affecting fire behavior and intensity, effects of fire on carbon storage, air chemistry, vegetation dynamics and structure, and forest health and productivity is needed before such considerations can be adequately addressed in regional planning. To monitor effects on a landscape scale, and to provide inputs into global and regional models of carbon cycling and atmospheric chemistry requires development of validated remote-sensing-based approaches to measurement of fire areas and fire severities.

The research has three major goals:

- To refine and validate preliminary methods for remote-sensing-based estimates of fire areas and fire severity for forests of central Siberia, by combining ground sampling of burned areas with medium-resolution (15-120 m.) and 1-km resolution satellite data.
- To develop improved data and models on effects of fire severity on fire emissions and on ecosystem damage and recovery for refining estimates of effects of fire regimes on carbon balance, greenhouse gas releases, and forest health and productivity.
- To combine experimentally-derived process data and models with the remote-sensing methods to develop regional estimates of fire areas, fire severity, and the impact of fire on carbon balance, emissions, and forest health.

The information and methods we are developing will provide the basis for recommendations on management of fuels, fire, and fire regimes to enhance carbon storage and sustainable forest management and to minimize negative impacts of fire on global environment, wood production, and ecosystem health.


**Keywords:** 1) Research Fields: biomass burning, carbon cycle, fire ecology, land cover classification, product validation; 2) Geographic Area/Biome: boreal forest, Russia; 3) Remote Sensing: aerial photography, AVHRR, LANDSAT, thermal IR; 4) Methods/scales: GIS, in-situ data, local scale, regional scale.

## Questions, Goals, and Approaches

**NASA ESE Scientific Questions addressed:** a) What are the changes in land cover resulting from fire (monitoring of fire area and severity from aircraft and satellite)? b) What are the causes of this land cover change (how does fire severity affect land cover change)? c) What are the consequences of fire-induced land-cover change on carbon cycling and ecosystem processes?

While this research does not include a specific social science component, it does address issues critical to resource-management decision-making; much of the success of accomplishing this type of research in Russia rest as much on understanding and working with social customs/habits and administrative structures of the country and the region as on the quality of scientific collaboration! Certainly 10-20% of our time is spent dealing with these aspects of the work. In terms of research themes, I would estimate Carbon: 30%; Water: 5%; Nutrients: 10%; GOFC: 40%; other (including fire behavior, ecosystem effects other than carbon, water, or nutrients): 15%.

**Overall Research Goals and Approach:**

- Combine ground data, aircraft data, and intermediate-resolution satellite data (ETM) to improve current AVHRR-based approaches for estimating the spatial extent of fires and to develop and validate methods to estimate spatial patterns of burn severity for forests of the Krasnoyarsk Region.
- Use ground data from replicated experimental fires to refine estimates of impacts of fire severity and seasonality on fire behavior, emissions, carbon storage, fuel dynamics, and ecosystem damage and recovery.
- Refine regional estimates of fire impacts on fuel dynamics, ecosystem processes, and carbon and trace gases by linking models developed from experimental data to spatial estimates of extent, intensity, and timing of fires.

**Goals for Year 2:**

- Conduct additional burns under varying fuel and climate conditions at the Yartsevo site. Completed.
- Acquire/build additional and replacement equipment needed for 2001 field season. Completed.
- Complete site preparation at Boguchani study site for burns in 2002. Completed. Due to continuing administrative problems with the leshoz, this site, on which plots had already been established and sampled, had to be abandoned. Sites have been selected in a nearby leshoz for preparation and burns in 2002.
- A) Fly over active fires with infrared camera as feasible; B) obtain intermediate resolution satellite data and ground truth data; C) conduct ground sampling on at least one site at each of three severity levels. A)-not completed in 2001 because we could not get the infrared instrument into the country; B) about 10 landsat ETM scenes were acquired for burned areas in the region. Analysis has begun and will continue in 2002; sites will be overflown or visited on the ground where possible, C) Ground sampling has been done on experimental sites at a range of severity levels from very low severity surface fires to high severity surface fires.
- Continue development and validation of active fire and fire scar mapping with AVHRR. Ongoing.
- Obtain additional funding to support exchange visits of Russian team members to the US and Canada. Completed.
- Hold PI meeting in Russia. PI meeting held in March 2001.

**ACCOMPLISHMENTS TO DATE**

This project has been in the planning and developmental stages since early 1996. Site selection and establishment on two experimental areas in the Krasnoyarsk Region and preliminary remote-sensing collaboration were supported by about $34k from the USDA Foreign Agriculture Service plus over $100k in contributed salaries, travel expenses, coordination meetings, site installation costs, and support of preliminary remote-sensing collaboration from the USFS, NASA, and the Canadian Forest Service. Plots were laid out and baseline data on soils, vegetation, and fuels collected prior to initiation of NASA funding. In addition, there were several exchange visits of Russian scientists to the US and Canada and North American scientists to Russia to discuss methods and collaboration and to select and install sites. Collaboration with the Sukachev Institute on development of remote sensing methods for fire area and severity began in 1991. Collaboration and support of the Russian Forest Service (Krasnoyarsk Region Forestry Committee, Avialesookhrana, and local leshozes and airbases) developed over several years is integral to the success of this program.

The 2001 progress report discussed Year 1 accomplishments, including: successful prescribed burns on two plots at our Yartsevo study site, acquisition of airborne digital infrared imagery over both prescribed fires and a large wildfire, development of consolidated data repositories in both Russia and Canada, and continued work on fire detection and mapping with AVHRR.

**Year 2 accomplishments:**

Based on our experience in the previous year, our Russian investigators ensured that all necessary permits and permissions were obtained before the beginning of the 2001 field season; baseline data collection on plots to be burned in 2001 was done in June and July, primarily by our Russian collaborators in consultation with Douglas McRae. McRae and Tom Blake (Canadian Forest Service) traveled to Krasnoyarsk for experimental burns in June and July at Yartsevo. Stephen Baker (FS-Missoula, MT), and Conard also participated in the July burns and data collection. A Russian study team remained on site for the entire two months. Deanne Shulman spent two weeks in Krasnoyarsk Region in August to assist with new site selection at Boguchany and discussions on site installation and layout.

- **Investigators have continued to exchange data and to tie their data collection to a common grid system, enabling excellent spatial correlation across databases. Centralized databases are now being maintained by both the Canadian Forest Service (McRae) and the Sukachev Institute (Ivanova and Sukhinin)**
- **Investigator meetings and e-mail communication are ongoing. A PI meeting and meetings with local and federal forestry officials were held in Russia in March 2001 to discuss operational concerns, data analysis, and preparation for the summer 2001 field season. Conard and Soja met with Sukhinin in the US to discuss details of the remote sensing work. North American participants met for two days in January 2002 for preliminary planning and budget discussions in preparation for a trip to Krasnoyarsk in February.** Sukhinin was able to visit the US in 2001 to take part in a NASA Earth Science Working Group meeting. During this visit, Conard, Sukhinin, and Soja participated in a workshop on fire remote sensing in boreal forests arranged by Eric Kasischke at the University of Maryland. After this visit Soja ordered ETM imagery for areas of active fires in 2000; some of this Sukhinin already has received; the rest will be delivered to him this month. The March 2001 meetings in Krasnoyarsk included half-day symposium at Sukachev Institute to present results, and several days of meetings with co-investigators and collaborators at the Natural Resources (Forestry) Committee and Avialesookhrana. We also met in Moscow with the science director for the Forestry Department and with representatives at the Canadian and US embassies.

- **Four 4-ha sites were burned at the Yartsevo site during June and July; burns ranged from very low intensity to moderate intensity surface fires (Figures 1, 2; Tables).** Plot 3 was initially ignited under conditions where fire did not carry; most of the plot was burned after further drying. Sampling conducted at all plots included: fuels, vegetation and stand structure, soil characteristics, small animal populations, insects, fire damage, fire behavior (ground measurements only); fire and soil temperature; emissions, and fire weather. We also conducted second-year sampling on Plots 13 and 14, which were burned in 2000. Figure 3 illustrates prefire and 1-year postfire conditions on these Plots. We have increased the accuracy of surface vegetation and fuel mapping and added mapping of downed logs to better understand and model fire behavior and emissions (Figure 4)
- **Twelve trees across the full diameter range up to 36-cm dbh were harvested and partitioned into various fuel components and size classes for developing biomass regressions.** These data will be critical both for quantifying above-ground carbon stocks from data on stand diameter and height distributions and for estimating combustion and emissions from crown fires.
- **Stephen Baker from Hao's group in Missoula designed improved sampling systems for fire emissions, which were deployed aerially in a helicopter and on the ground during the July burns. Yuri Samsonov and Andrei Ivanov sampled particulate carbon from the air and on the ground using a dual filter system designed for this purpose (Figures 5 and 6).** These systems worked well and enabled us to sample smoke under a range of burning conditions and surface fuel types.
- **A new thermocouple deployment system designed by Valeri Ivanov allowed thermocouples to be suspended on a wire between trees to minimize surface fuel disturbance in areas of temperature measurements.** This is particularly important where lichens dominate surface fuels as even light trampling can easily destroy the lichen structure. In collaboration with Olga Zubareva, we also measured temperature penetration into the bark of selected trees during fires to improve our understanding of the mortality responses of Scotch pine to fire.
- **Analysis has continued of infrared images from 2000. With the help of Ji-zhong Jin (University of MD) we have a preliminary registration of fire spread and temperature data with the underlying ground data (Figure 7) and mapped fire temperatures and rates of spread (Figure 8). These data will enable direct correlation of vegetation and fuel characteristics with fire intensity and residence time.** Both the North American and Russian teams now have all the infrared data obtained in 2000. Analysis of wildfire data continues and is being carried out primarily by Sukhinin. Because of the difficulty of transmitting image files via Internet, we expect to obtain additional analyzed data on our visit to Krasnoyarsk later this month.
- **By combining fuels, fire weather, and fire behavior data we can now quantify weather parameters (Table 1) and Russian and Canadian Fire Danger Rating indices (Table 2), and calculate fuel consumption (Table 3), carbon release (Table 4), and fire behavior characteristics (Table 5).** These data show clearly the impacts of weather and fuel condition on fire behavior and subsequent carbon emissions. On the relatively uniform plots in our study site, estimated fuel consumption ranged from 0.65 to 2.12 kg/m$^2$, and carbon release from 3.25 to 10.61 t/ha. Preliminary equations relating various components of the Canadian and Russian fire danger rating systems to fuel consumption and carbon release have $r^2$ ranging from 0.71 to 0.98 (Table 6). In what we believe is a novel approach, we intend to use these relationships in combination with remotely-sensed data on fire areas and severity to estimate regional fire emissions.
- **New study sites are being selected to replace the original site in the Boguchani area.** During a site visit to Gremuchinsky Leshoz in August, Ivanova, Ivanov, and Shulman made the difficult decision to abandon the Boguchani area site because of continuing administrative problems. Through the support of the Krasnoyarsk Forestry Committee, however, they were able to identify a

nearby leshoz (Govorkovo) with more cooperative management and to select the first of several potential experimental plots for use starting in 2002.

- **Additional funding ($50,000/year for two years) was recently obtained from the Civilian Research and Development Foundation to support salaries and exchange visits for Russian collaborators.** This will supplement and replace funds formerly obtained from the Forest Service or cut from our NASA budget when funding was reduced below the requested level.
- **Cooperation has begun with Mark Finney at the USFS Fire Laboratory in Missoula, MT on using our data to evaluate the performance of FARSITE, a landscape fire behavior modeling system.** The ultimate goal will be to parameterize the model so it works well for the boreal Scotch pine systems.
- **Hao's group in Missoula has hired a new remote sensing specialist to help with image analysis.**

<u>**Highlights of accomplishments include**</u>:

- **Five prescribed burns were conducted at varying intensities in June and July 2001.**
- **Improved sampling systems enabled sampling of both particulates and gaseous emissions from helicopter and on the ground.**
- **Twelve trees across the full diameter range were harvested and partitioned into various fuel components and size classes for developing biomass regressions.**
- **Most summer 2001 field data have been analyzed and exchanged between North American and Russian partners.**
- **By combining fuels, fire weather, and fire behavior data we can now quantify Russian and Canadian Fire Danger Rating indices and calculate fuel consumption, carbon release, and fire behavior characteristics. These data show impacts of weather and fuel condition that lead to three-fold differences in subsequent carbon emissions.**
- **Preliminary equations relating components of the Canadian and Russian fire danger rating systems to fuel consumption and carbon release show great promise for combining this approach with remote sensing data on fire areas to accurately estimate regional fire emissions**.
- **A study site large enough for several plots was selected on the Govorkovo Leshoz (Boguchani study area) to partially replace the Gremuchinsky site. Additional sites will be identified in 2002.**
- **Analysis and methods development continued for estimating burned area from active fire and fire scar pixels on AVHRR and Landsat ETM. A manuscript has been prepared on these methods.**
- **A PI meeting and meetings with local and federal forestry officials were held in Russia in March, 2001 to discuss data analysis and prepare for the summer 2001 field season. North American participants met for two days in January 2002 for preliminary planning and budget discussions in preparation for a trip to Krasnoyarsk in February.**

**CONCLUSIONS**

Overall, we feel that the project is making good progress. Our mutual collaboration with Russian investigators has been excellent, including continued data-sharing and increased collaboration on analysis. For the 2001 field season, we had the required official permissions for use of the land, for burning, and for aircraft remote-sensing thanks in large part to the tireless efforts of our Russian collaborators. We also are more aware of the restrictions under which we must operate regarding aircraft-based activities and have adjusted to them by training Russian collaborators on all equipment that is operated from aircraft (cameras as well as equipment for emission sampling).

As anticipated in last year's report, a change in administration and other factors led us to decide to abandon use of the site on Gremuchinsky leshoz as our Boguchani area site. Despite previous formal agreements on use of the land, it became clear that we would not have the level of cooperation necessary to carry out this research. Nonetheless, due to good cooperation from regional forestry officials, we were able to rapidly identify new sites in the Boguchani area.

A continuing challenge is bringing equipment and samples into and out of Russia. We had some problems with the infrared video camera in 2000, which we thought had been resolved for 2001. However, despite a slew of official paperwork, we were never able to get the camera into the country in 2001. We now are working out the details for renting a camera in Russia for the summer 2002 season. This should solve the problems of past years. We also tried to follow proper procedures for shipping equipment into the country last year, but it still was held up in customs for over a month in Novosibirsk and in Krasnoyarsk before we were able to get it released (many hours of Sukhinin's time and a few dollars in storage fees!). Even with the best of care, it appears that the best insurance is to allow at least 2 months for equipment to get through customs.

Despite the difficulties of working in Russia, this project continues to make excellent progress. We are developing the most comprehensive data on fire emissions, behavior, and ecosystem effects ever collected in the boreal zone, and probably one of the best anywhere in the world. We will continue to build this data set through more experimental fires, overflights of wildfires, and analysis of multi-scale remote sensing data. While we will not have the full number of experimental burns originally hoped for, we are obtaining excellent data on fires with a diversity of characteristics. One weakness is that we do not expect to conduct more than one or two burns in the second study area this summer. The applicability of our results over broad areas will be much improved if we are able to obtain funding for an additional 1-2 seasons of burning and fire monitoring and to measure ecosystem responses for several years after fires. This would consist primarily of burns in the Govorkovo area, and additional work with wildfires--and would complement our new 2-year grant from CRDF. However, even within the duration of the current agreement, we anticipate that we will substantially meet project objectives.

**Publications and manuscripts**:

Conard, Susan G., Anatoly I. Sukhinin, Donald R. Cahoon, Eduard P. Davidenko, Brian J. Stocks, and Galina A. Ivanova. *Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia.* Climatic Change (in press).

Soja, A. J., Sukhihin, A., Cahoon, D.R., Shugart, H.H., and Stackhouse, P.W. *Frequency and distribution of fire in Siberia described using an AVHRR-derived fire product* (draft manuscript).

Sukhinin, Anatoli. *Fire detection algorithm for Krasnoyarsk NASA/HRPT receiving station*. Draft manuscript.

**FIRE BEAR RESULTS**
(2000-2001 field season)

Table 1. Fire weather parameters measured at the time of each experimental fire.

| | | | Weather parameters | | | |
|---|---|---|---|---|---|---|
| Fire No. | Date (dd/mm/yyyy) | Ignition time (LST) | Temperature (°C) | Relative humidity (%) | Wind (km/h) | Rain (mm) |
| 2 | 19/06/2001 | 18:00 | 27.0 | 32 | 10.2 | 2.0 |
| 3a | 24/06/2001 | 17:00 | 14.1 | 95 | 3.6 | 0.7 |
| 3b | 26/07/2001 | 15:00 | 18.2 | 43 | 9.7 | 1.0 |
| 6 | 30/07/2001 | 14:00 | 22.4 | 52 | 2.6 | 0.0 |
| 13 | 26/07/2000 | 16:30 | 24.2 | 45 | 3.6 | 0.0 |
| 14 | 18/07/2000 | 15:00 | 26.4 | 21 | 1.0 | 0.0 |
| 19 | 28/07/2001 | 15:00 | 21.2 | 40 | 0.8 | 0.0 |

Table 2. Russian Fire Danger System and Canadian Forest Fire Weather Index (FWI) System component values associated with each experimental fire.

| | Russian Fire Danger System* | | Canadian Forest Fire Weather Index (FWI) System components# | | | | | |
|---|---|---|---|---|---|---|---|---|
| Fire No. | Nesterov Index | Moisture Index | FFMC | DMC | DC | BUI | ISI | FWI |
| 2 | 2045 | 1583 | 84.9 | 16.9 | 104 | 24.0 | 3.4 | 6.3 |
| 3a | 461 | 470 | 73.7 | 27.4 | 193 | 40.4 | 0.9 | 1.8 |
| 3b | 207 | 297 | 76.0 | 18.9 | 189 | 30.2 | 1.3 | 2.6 |
| 6 | 561 | 651 | 88.1 | 28.2 | 217 | 42.6 | 3.7 | 9.5 |
| 13 | 1170 | 1273 | 89.2 | 36.1 | 401 | 58.9 | 4.0 | 12.2 |
| 14 | 2093 | 2421 | 92.8 | 50.5 | 393 | 76.4 | 8.5 | 24.7 |
| 19 | 1034 | 1124 | 86.9 | 23.4 | 202 | 36.4 | 2.8 | 6.8 |

* based on 1300 LST weather.

# based on weather at ignition (see Table 1).

Table 3. Impact of experimental fires on fuel consumption (kg/m$^2$).

| Fire No. | Down woody fuel consumed | Litter consumed | Duff consumed | Crown fuel consumed | Total Consumption |
|---|---|---|---|---|---|
| 2 | 0.0342 | 0.098 | 0.7017 | 0.0 | 0.8339 |
| 3a* | - | - | - | - | - |
| 3b | 0.0281 | 0.1854 | 0.4372 | 0.0 | 0.6507 |
| 6 | 0.0620 | 0.1814 | 0.5908 | 0.0 | 0.8342 |
| 13 | 0.3998 | 0.0130 | 0.7983 | 0.0 | 1.2111 |
| 14 | 0.4378 | 0.0256 | 1.6581 | 0.0 | 2.1215 |
| 19 | 0.0547 | 0.1782 | 0.4765 | 0.0 | 0.7098 |

* Because Fire 3a was extinguished before any fuel sampling plots were consumed, there are no quantitative measurements of actual fuel consumption for this fire.

Table 4. Impact of experimental fires on carbon release (t/ha).

| Fire No. | Down woody fuels | Litter | Duff | Crown fuels | Total carbon release |
|---|---|---|---|---|---|
| 2 | 0.171 | 0.490 | 3.509 | 0.0 | 4.170 |
| 3a* | - | - | - | - | - |
| 3b | 0.141 | 0.927 | 2.186 | 0.0 | 3.254 |
| 6 | 0.310 | 0.907 | 2.954 | 0.0 | 4.171 |
| 13 | 1.999 | 0.065 | 3.992 | 0.0 | 6.056 |
| 14 | 2.189 | 0.128 | 8.291 | 0.0 | 10.608 |
| 19 | 0.274 | 0.891 | 2.383 | 0.0 | 3.548 |

* Because Fire 3a was extinguished before any fuel sampling plots were consumed, there are no quantitative measurements of actual carbon releases for this fire.

Table 5. Fire behavior characteristics of the Yartsevo experimental fires in Scotch pine (*Pinus sylvestris*) .

| Fire No. | Depth of burn (cm) | Rate of spread (m/min) | Fireline intensity (kW/m) |
|---|---|---|---|
| 2 | 4.4 | 4.9 | 1394 |
| 3a | - | 0.6 | 89* |
| 3b | 3.3 | 2.5 | 372 |
| 6 | 4.0 | 5.9 | 1684 |
| 13 | 4.7 | 2.0 | 828 |
| 14 | 6.4 | 9.0 | 6513 |
| 19 | 3.5 | 2.9 | 703 |

* Fireline intensity calculations for Fire 3a was based on fuel consumption estimated from Fire 3b.

Table 6. Preliminary equations relating environmental variables for fuel consumption, carbon release, and fire behavior characteristics.

| | |
|---|---|
| DoB = 2.13 + .08 DMC | $R^2$ = 0.76 |
| DoB = 2.68*exp(0.20*DMC) | $R^2$ = 0.81 |
| DuffC = 0.26*exp(0.03*DMC) | $R^2$ = 0.89 |
| WFC = -0.2188 + 0.0015DC | $R^2$ = 0.90 |
| WFC = 0.0078*exp(0.0098*DC) | $R^2$ = 0.98 |
| CR = 1.86*exp(0.03*DMC) | $R^2$ = 0.96 |
| RoS = 0.47 + 1.00*ISI | $R^2$ = 0.76 |
| RoS = 1.18*exp(0.27*ISI) | $R^2$ = 0.71 |
| RoS = 0.76+1.03*ISI | $R^2$ = 0.90 (without Plot 13) |
| FI = 222.7*exp (0.14FWI) | $R^2$ = 0.94 |
| FI = 229.51*exp(0.15FWI) | $R^2$ = 0.96 (without Plot 13) |

DoB: depth of burn (cm); DuffC: duff or forest floor consumption without the litter layer (kg/m2); WFC: down dead woody fuel consumption (kg/$m^2$); CR: total carbon release (t/ha); RoS: rate of spread (m/min); FI: fireline intensity (kW/m); DMC: Canadian Duff Moisture Code; DC: Canadian Drought Code; ISI: Canadian Initial Spread Index; and FWI: Canadian Fire Weather Index.

Figure 1. Fires in Plots 14 (high-intensity surface fire from July 2000) and 3b (low-intensity surface fire from July 2001)

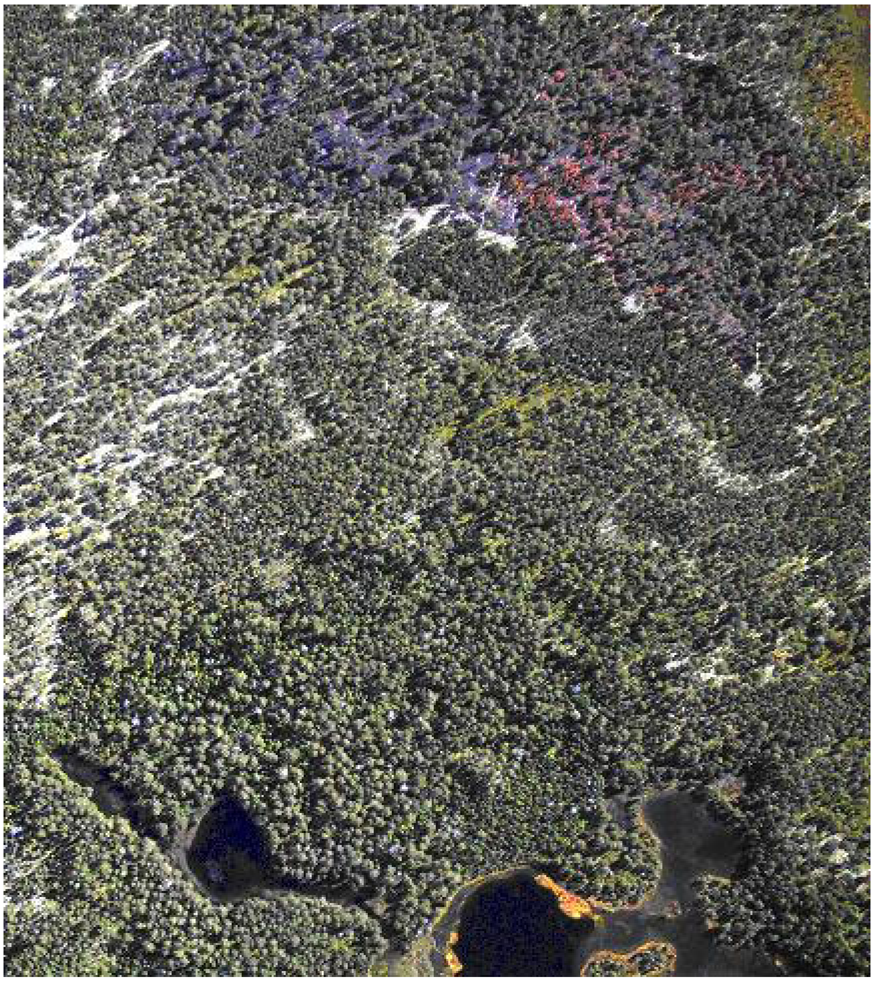


Figure 2. An aerial image of the Yartsevo site during the summer of 2001. Experimental fires on plots 2 (right) and 3 (left side) can be seen at the upper right hand corner of the image. Tree crown scorch (which will result in mortality) can be observed on Plot 2 because of higher fireline intensities. The left-hand side of the image shows the openness common in drier areas of Scotch pine forest in Siberia where patches of lichen on the ground (light areas) can be easily seen. This open stand structure prevents the development of crown fires except under very severe fire danger.

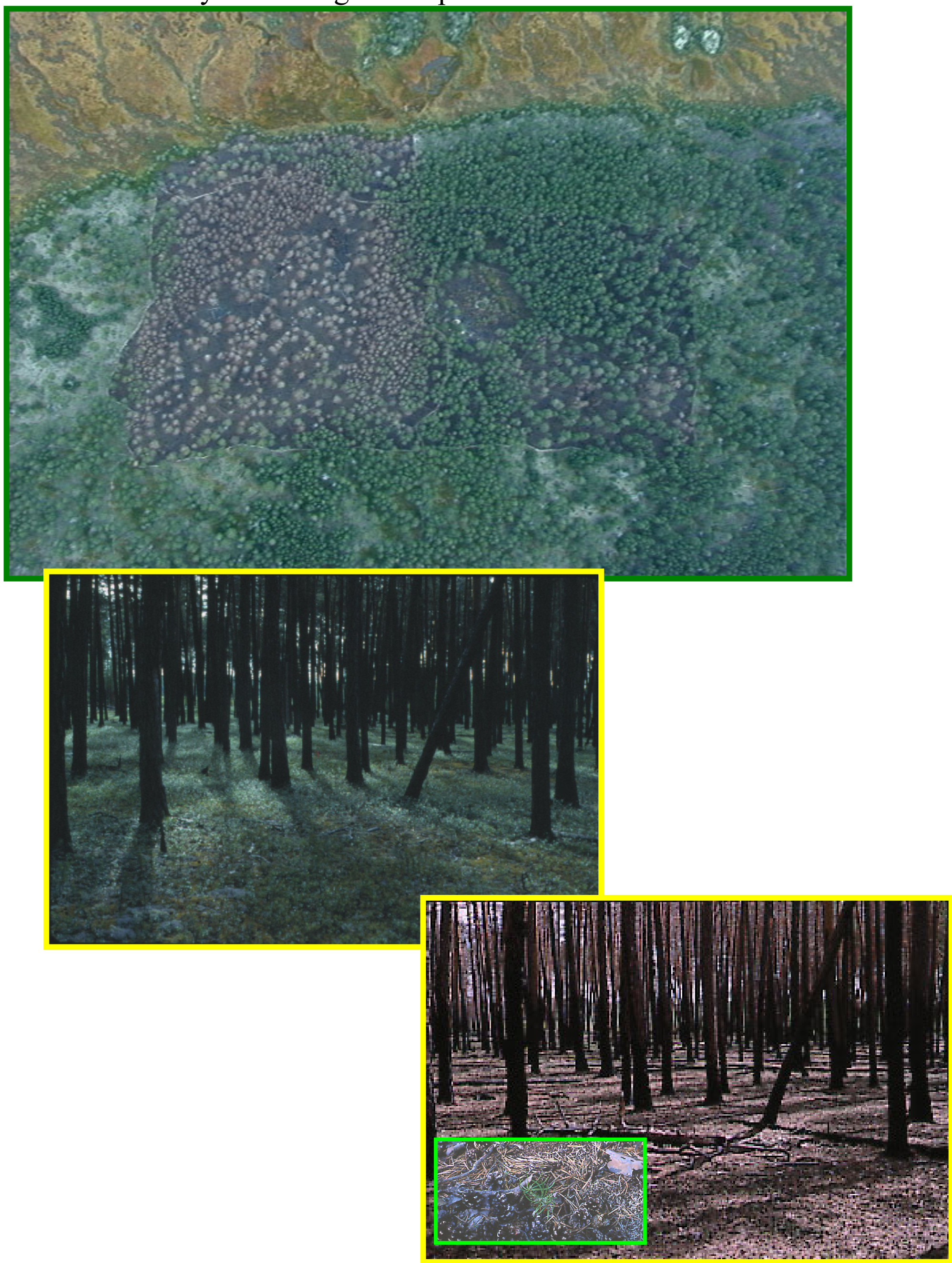


Figure 3. Views of plots burned in 2000. Top—aerial view of Plot 14 (left) and Plot 13 (right) one year after burning. Below—Plot 14 before and one year after burning. Inset shows enlarged view of forest floor with seedling regeneration.

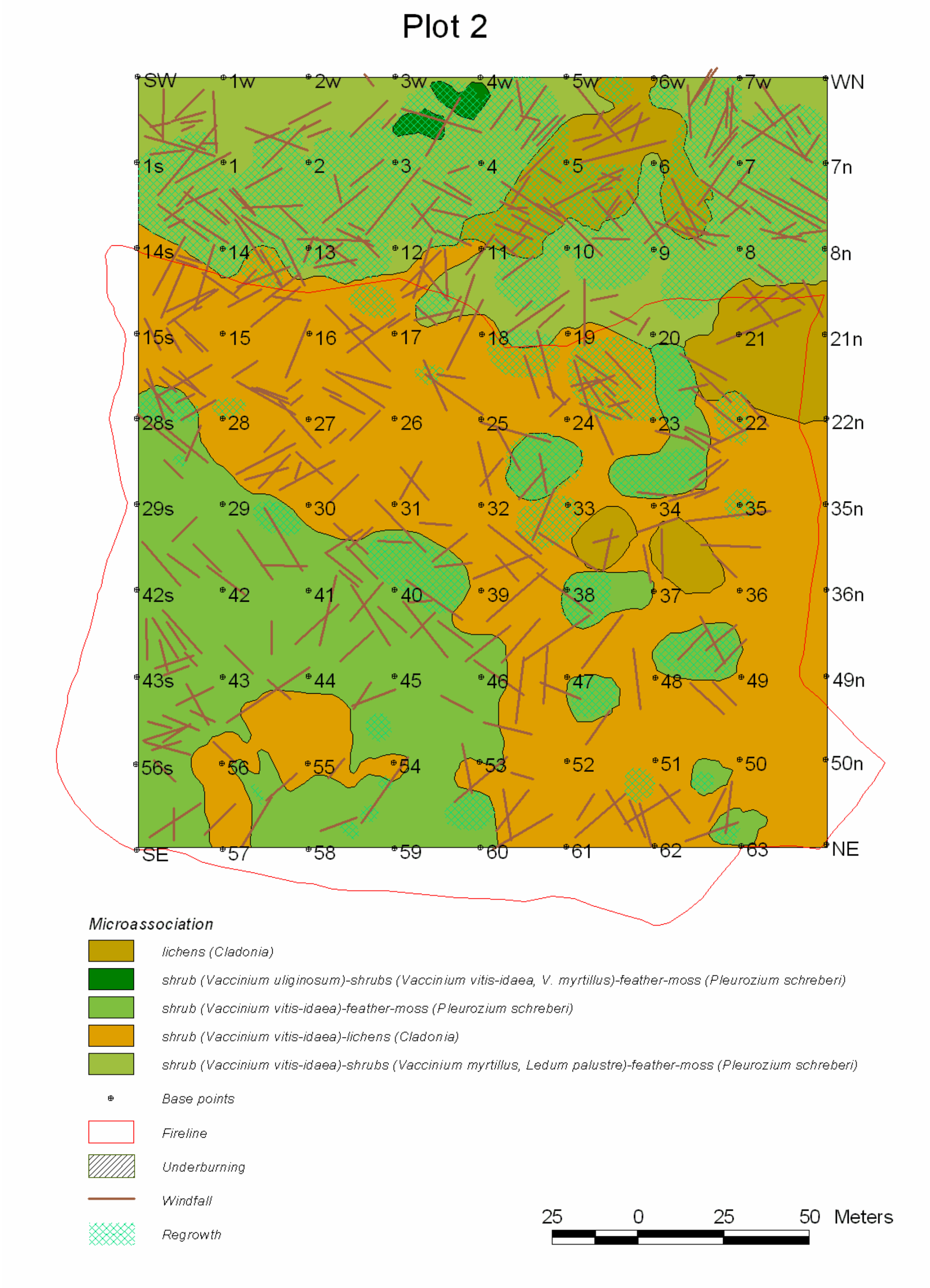
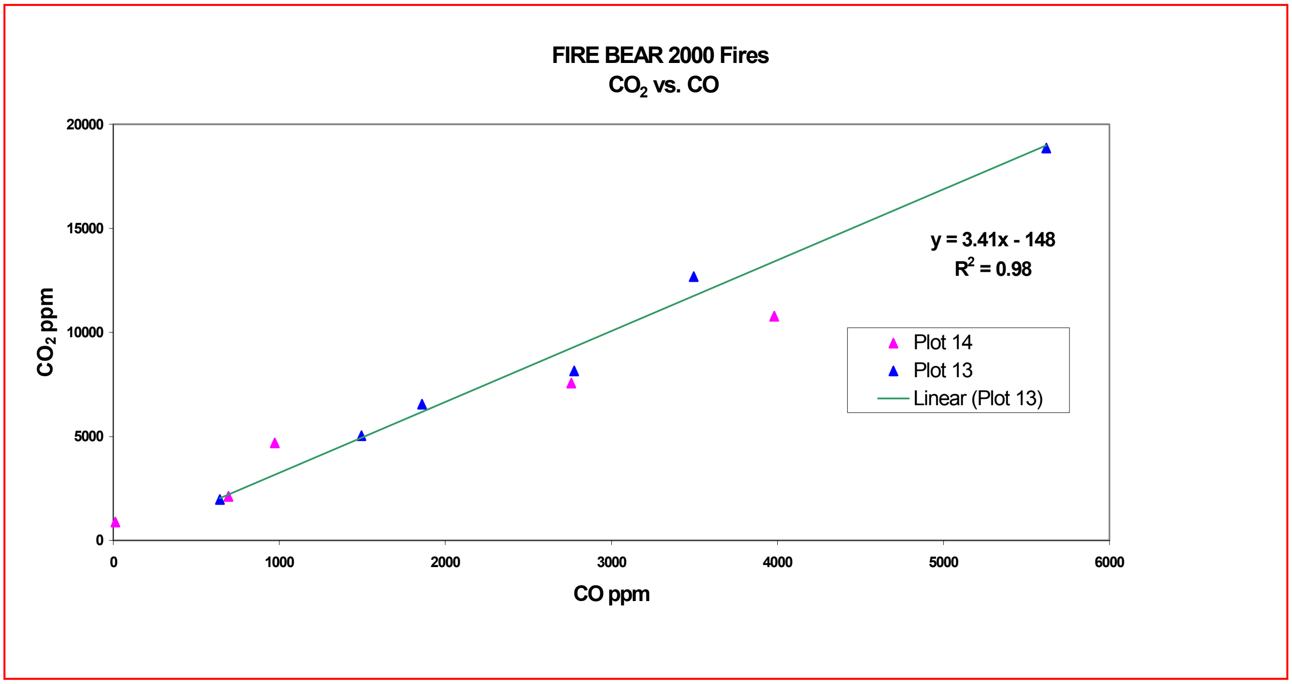



Figure 4. Surface vegetation/fuel map of plot 2 before burning. Map shows grid reference points, the actual area burned (red line), and major surface vegetation, including patches of regeneration--as well as downed tree trunks, which are very important for surface fire spread, especially with a low intensity fire.

Figure 5. Smoke sampling with newly designed field samplers in July 2001. Top—sampling for carbon and particulates. Bottom—sampling for gases. With this equipment we can sample smoke from specific fuel types and differentiate smoke from flaming and smoldering combustion phases.



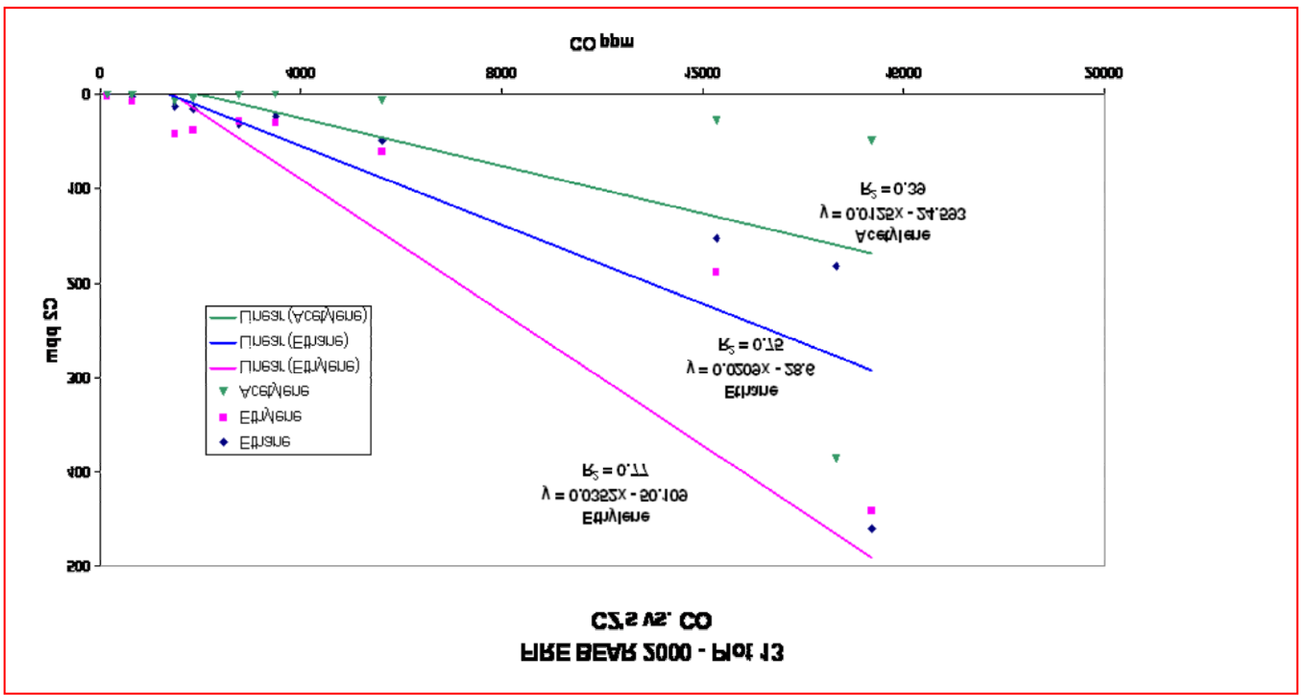




Figure 6. Sample emission data from summer 2000 ground-based sampling of gases.

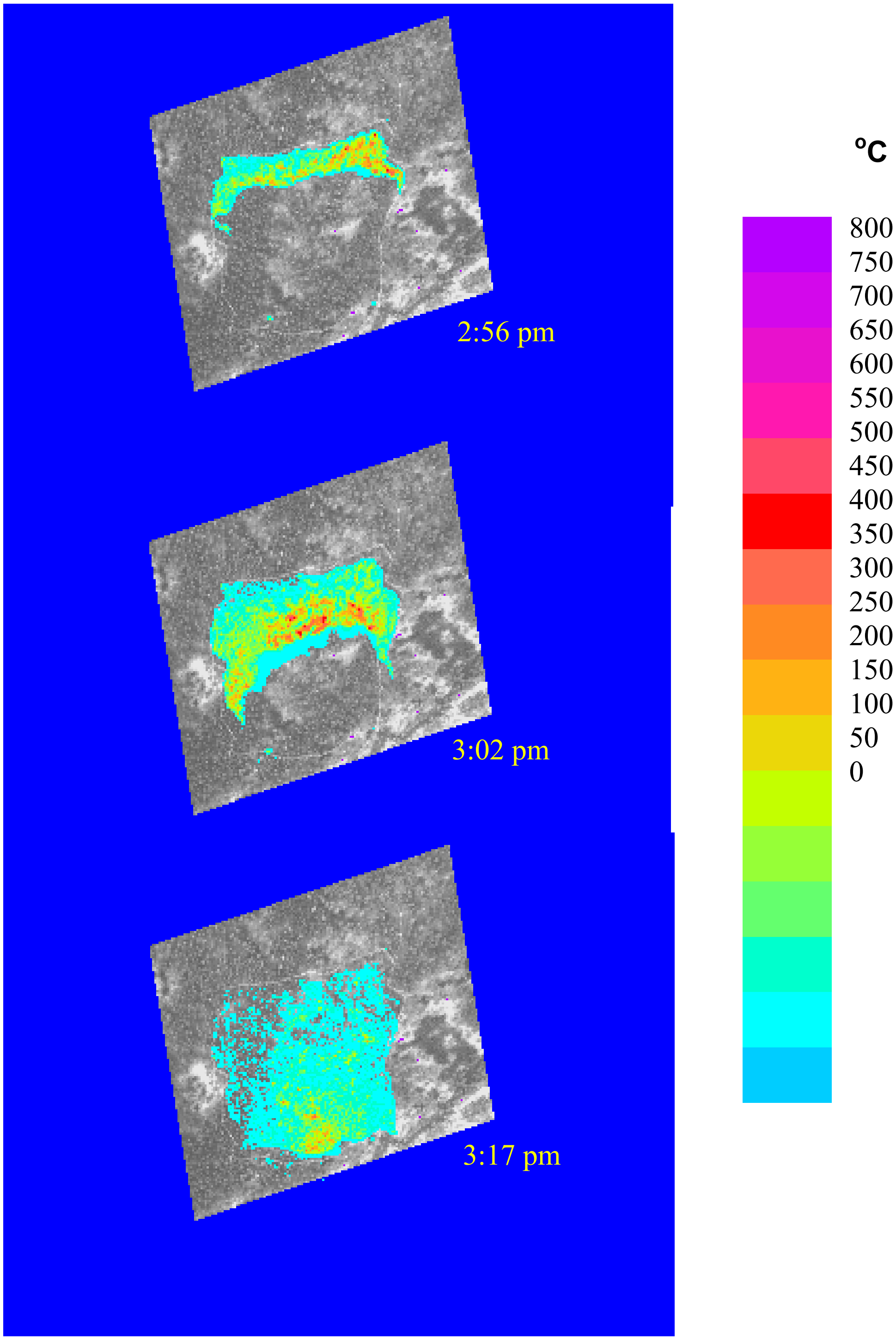



Figure 7. Fire remote sensing data from IR camera showing progression of fire overlaid on aerial photograph of site (Plot 14, July 18, 2000). Legend at right shows temperatures in °C.

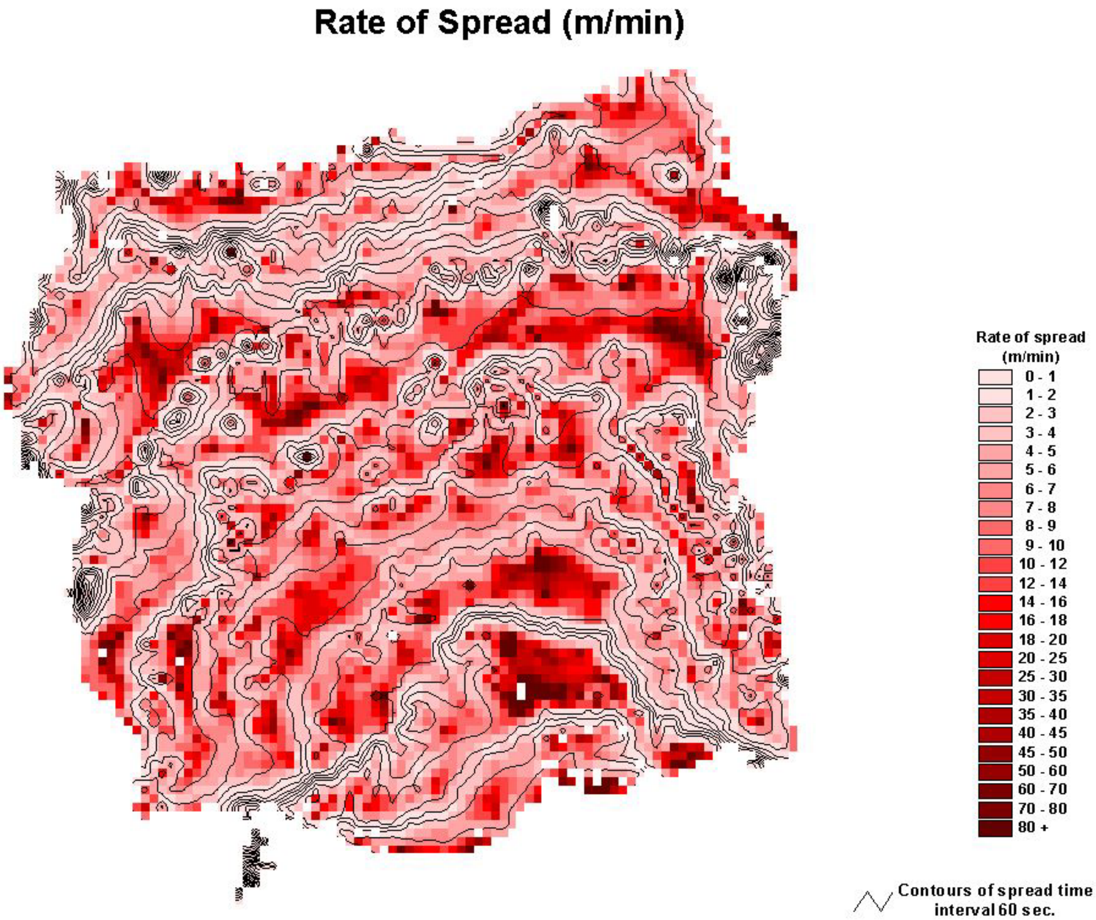



Figure 8. Mapped rates of spread for fire on plot 14 (July 18, 2000) based on data from aerial infrared video camera. These data, along with fireline intensity and residence time, will enable us to better understand and model fire effects and fuel consumption across the plots.